

Real-time on-board orbit determination with DORIS

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J.-P. Berthias, C. Jayles, D. Pradines

Centre National d'Etudes Spatiales
18 Av. Edouard Belin
31055 TOULOUSE CEDEX
FRANCE

Abstract: A space borne orbit determination system is being developed by the French Space Agency (CNES) for the SPOT 4 satellite. It processes DORIS measurements to produce an orbit with an accuracy of about 50 meters rms. In order to evaluate the reliability of the software, it was combined with the MERCATOR man/machine interface and used to process the TOPEX/Poseidon DORIS data in near real time during the validation phase of the instrument, at JPL and at CNES. This paper gives an overview of the orbit determination system and presents the results of the TOPEX/Poseidon experiment.

Introduction:

Autonomous control of a satellite's orbit is an attractive concept which offers many advantages. Under the control of an on-board program, the optimum firing of the thrusters maintains the spacecraft on an orbit which has been pre-programmed. Meanwhile on-board instruments use the knowledge of the position and velocity of the spacecraft to orient themselves or pre-process their measurements. On the ground, operators at a simplified control center use telemetry data to verify the proper behavior of the spacecraft.

Partial autonomy is already achieved by all satellites. Attitude control is a nearly completely automated task which is under the control of an on-board program. Since orientation measurements are performed by the spacecraft itself, and a short response time is necessary, the automation of attitude control is not only convenient but practically indispensable. On the other hand, until the last few years, the data necessary for precise navigation could only be obtained on the ground and required lengthy processing. Thanks to advances in the stability of on-board clocks, new on-board tracking systems including GPS and DORIS are now available. With these instruments the accurate measurements needed to compute the position and velocity of the spacecraft are available on-board, thus opening the door to automated navigation.

As a first step in this direction, the French Space Agency, CNES (Centre National d'Etudes Spatiales) decided to pursue the subject of on-board orbit

determination. First, a feasibility study was conducted in collaboration with Aérospatiale and Dassault Electronique. It demonstrated the possibility of computing the orbit of a low altitude satellite equipped with a DORIS receiver, using only a small program and limited computing resources. Following this success, it was decided to fly an on-board orbit determination system on the Earth observation satellite SPOT 4, and the DIODE project was thus created. Some details of this system will be given in this paper.

The presence of a DORIS receiver on TOPEX/Poseidon provided us with an opportunity to test the current version of the software in a new environment and validate some of our assumptions. In return, it offered a quick-look approach to the TOPEX/Poseidon DORIS orbit and a immediate appraisal of the performance of the instrument.

DORIS:

The DORIS system, developed jointly by CNES, the French National Geographic Institute, IGN (Institut Géographique National) and the GRGS (Groupe de Recherches en Géodésie Spatiale), uses a global network of ground beacons which broadcast omnidirectionally on two frequencies, 2036.25 and 401.25 MHz. Each beacon contains an ultrastable quartz oscillator with a stability of about $5 \cdot 10^{-13}$ for periods of 10 to 100 seconds. In addition, two master beacons, one in Toulouse and one in Kourou, are tied to atomic clocks. The DORIS instrument carried by

the spacecraft contains a dual frequency receiver and an ultrastable oscillator. It computes the Doppler shifts and the time of arrival of the time synchronization signals. The overall system noise is lower than 0.3 mm/s [1].

The instrument computes the Doppler count at both frequencies every 10 seconds when a beacon is in view. In nominal operation mode, the receiver is programmed to listen to specific beacons, one beacon at a time.

The orbital coverage provided by the extensive beacon network is over 70 % for the SPOT satellites (800 km altitude) and reaches 85 % for TOPEX/Poseidon (1330 km altitude).

Implementation:

To accommodate the on-board orbit determination software, Dassault Electronique, which manufactures the DORIS receiver, has added a new card to the instrument. This new card carries a Marconi MAS 281 microprocessor, which follows the MIL STD 1750A standard, and 48 kwords of available memory. The clock rate is 10 MHz. EDACs are used to detect and eliminate memory upsets.

The memory of the new card is seen by the DORIS receiver as part of its memory. This allows for easy loading of the software while in flight, and permits the use of reserved memory locations for an interface between the receiver and the orbit determination system (cf Fig. 1).

The orbit determination software is being developed by CNES. It runs under the supervision of the navigation management software written by Dassault Electronique, which is responsible, among other things, for the interrupt driven interface with SPOT 4.

Both sets of software are written in Ada. The orbit determination program is designed following the Hierarchical Object Oriented Design (HOOD) method. With the help of the CNES Ada group, STOOD, a HOOD implementation tool developed by TNI, has been used to design and write the software.

The result is a 2400 line long code which is easy to maintain and update. When compiled for the 1750 target microprocessor using the VAX based TLD cross-compiler, the code and data occupies about 32 kwords.

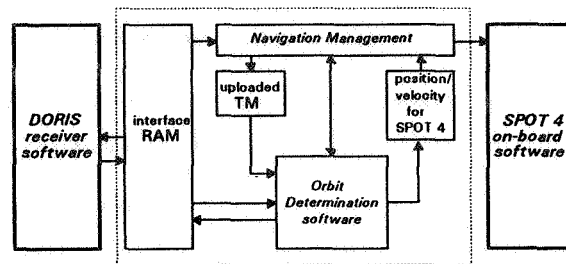


Fig. 1 - System architecture

Principle of operation:

Once an initial state vector has been uploaded, the function of the on-board orbit determination program is to update it every ten seconds. As the DORIS measurements are performed on-board, they are dated in instrument time, and a correspondence between instrument time and TAI has to be maintained to provide properly dated state vectors.

Two separate Kalman filters are used to fulfil these functions. The first filter computes the difference between instrument time and TAI. This value, modeled as a constant, is updated when synchronization measurements are performed while flying over a master beacon. The second filter updates a state composed of the spacecraft position and velocity and a frequency bias for the current pass when measurements are performed. This filter is written using Bierman's UD formulation.

The tuning parameters for both filters can be modified by ground commands.

When the navigation management software activates the orbit determination function, it provides the date at which the state is to be computed and the list of uploaded parameters to process. The date is equal to the TAI time of the end of the preceding cycle, rounded to an even multiple of 10 seconds.

After activation of the orbit determination function by the navigation management software, the schedule of operations is as follows:

- 1) If uploaded parameters are present, they are taken into account, and the values of the corresponding parameters are modified.
- 2) The current state is extrapolated to the desired date. The extrapolation is performed by a fourth order Runge-Kutta integrator using the space efficient Gill formulation.

3) If measurements are performed over a master beacon, the difference between instrument time and TAI is updated.

4) If measurements are performed, the predicted value and the residual are computed. If the residual is lower than the acceptance threshold, the measurement is used to update the state.

All these operations are performed in less than five seconds.

If for some reason the orbit navigation function has not been activated over a few cycles, at the next call the difference between the date at which the state should be computed and the date of the current state can be large. As a maximum of five steps can be performed per call, it can take many calls for the system to catch up. During this interval, no measurement is processed and no result is provided to the user.

Models:

DORIS, a Doppler based tracking system, measures relative velocities. To relate the measured data to the spacecraft position, an integration of the equations of motion is required. Hence, a force model is necessary.

Due to the excellent orbital coverage, periods during which the extrapolated position is not corrected by a measurement are very short. Therefore errors due to limitations in the force model cannot grow large. The current force model is limited to a dedicated sixth order and degree gravity field provided by the GRGS. This choice satisfies the accuracy requirements and reduces the memory requirement to a minimum. Third body perturbation and drag models have been developed, and could be easily included in the software if the mission justified it and if space was available.

As the acceleration model is rudimentary, the model covariance input to the filter is large. This in turn gives a lot of weight to the measurements. The orbit is data driven, and this can be useful when an unexpected force is present. Least squares based standard orbit determination software cannot handle unmodeled forces, while this system can. In this respect, this system produces results similar to those of a partly dynamic and partly geometric analysis.

Measurement models are also very simple. Dual frequency ionosphere correction is applied to the data. A basic troposphere delay correction, assuming a constant vertical electron content, is also applied. The

Earth orientation model is almost non-existent: no correction is applied for precession, nutation, or polar motion. The Earth rotation rate is assumed constant and UTC is used in place of UT1 to compute the hour angle. Beacon locations are memorized in an on-board table which can be updated by ground commands.

The choice of these models has been validated by processing many samples of SPOT 2 DORIS data. In particular, studies proved that the accuracy requirements are met even in the presence of the increased drag due to high solar activity or of frequent thruster firing such as periods when the spacecraft goes into safhold mode [2].

The TOPEX validation experiment:

The launch of TOPEX/Poseidon on 10 August 1992 provided an excellent opportunity to test the behavior of the orbit determination component of the system. Processing data from a new instrument is useful to ensure that no assumptions were made that are unique to the SPOT 2 configuration.

Also, the high level of spacecraft activity between the launch and the transfer into nominal orbit requires the transmission to the software of many parameters, such as maneuver characteristics.

It was therefore decided to run the software in near real time to process the TOPEX/Poseidon DORIS data both at JPL and at CNES. The environment for the orbit determination program was provided by MERCATOR.

MERCATOR is regularly used by CNES to put geostationary satellites in orbit [3]. It runs on SUN workstations and offers a framework within which technical modules can easily be included and activated. It was successfully employed for ten missions between April 1989 and September 1992. It is therefore a solid and reliable software which is ergonomically adapted to the needs of orbital mechanic engineers.

For the TOPEX/Poseidon experiment MERCATOR was used to

- decommutate the telemetry and supply the data in a form similar to that coming out of the DORIS instrument
- provide a user friendly interface
- permit the rapid analysis of results using auxiliary calculations and graphical tools

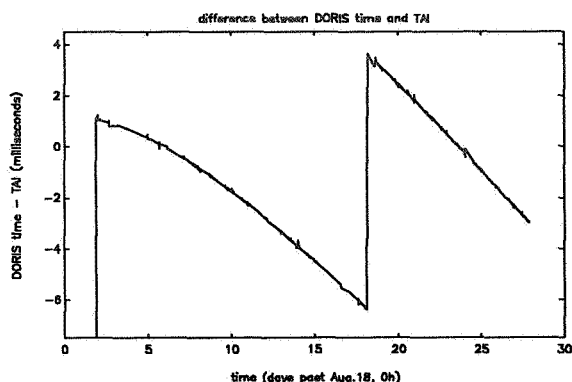


Fig. 2 - Time synchronization

Telemetry from the DORIS instrument on the TOPEX/Poseidon spacecraft is recorded on-board and then played back to Earth via TDRSS. From this data the TOPEX/Poseidon Ground Segment generates a Selected Telemetry Record (STR) file daily. These files are then copied to the CNES control center via an electronic network.

For our experiment, we could access these files both at JPL and at CNES. After the first few days, once a file was copied to our SUN, it took about half an hour to produce an ephemeris.

In addition to this regular operation mode, we also processed special request STRs at JPL, using initial state vectors provided by the TOPEX/Poseidon navigation team. We were then able to produce short arc ephemerides only one to two hours after the acquisition of the data. This was especially helpful to check the state of the instrument after major operations (reset of the clock, change in the mode of operations, etc.).

Overall, the quality of the results exceeded our expectations. In one instance, we had to integrate over an eight hour data gap, and were amazed to see the filter locked back on the right orbit on the first subsequent pass. Note that this would probably not be possible for the lower altitude SPOT spacecraft.

In order to more accurately reproduce the conditions of on-board operations, we have reprocessed in a single batch the first 28 days of DORIS data following the second reset of the instrument clock. The uploaded parameters were the initial conditions, the date of the reset of the clock, the value of UTC minus TAI, and the pre-execution values of the five maneuvers (CAL, INC, IPM1, IPM2, IPM3) [4]. With this limited set of inputs, the orbit determination software produced the results shown below.

Figure 2 shows the difference between DORIS time and TAI as computed by our orbit determination software using synchronization measurements performed over the Toulouse master beacon. The curve clearly shows the clock adjustment of Aug. 19 followed by the slow drift of the DORIS time. Note that at first the oscillator drifts, but, as the oscillator reaches a stable state, the difference becomes linear, due to the fact that the oscillator frequency is not exactly nominal. On the 18th day, an automated clock correction brought the DORIS clock back to TAI. The error level in the time determination is at the level of a few tenths of milliseconds. This corresponds to a meter size error on the orbit in the along-track direction. Therefore, the time synchronization is not a limiting factor on the orbital accuracy.

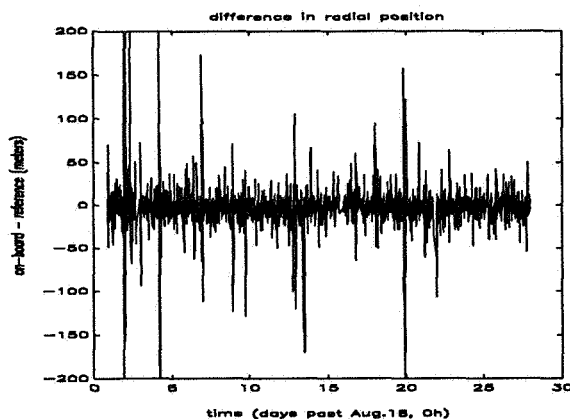


Fig 3 - Radial difference

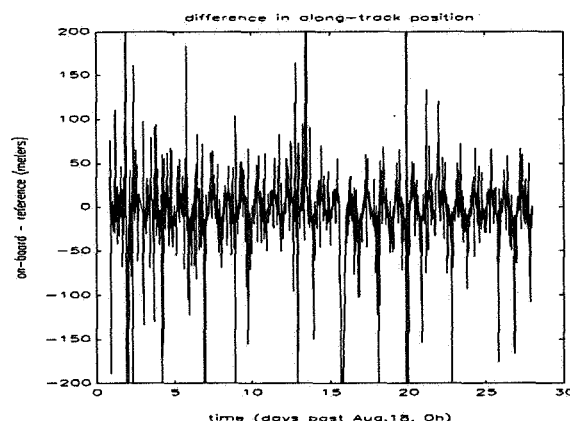


Fig 4 - Along-track difference

Figures 3 and 4 show differences between the "on-board" orbit and a reference orbit obtained by processing the DORIS data with the ZOOM software [5]. The precision level of the reference is better than one meter.

The standard deviations corresponding to figures 3 and 4 are 20 and 44 meters respectively. The overall standard deviation of the distance to the reference orbit is 53 meters. These results are therefore within the requirements of the SPOT 4 project.

However, a few accidents contributed greatly to increase these statistics. In particular, this test showed us that our software does not properly handle forced clock resynchronizations, such as the one which happened on August 19. As these occur only after a restart of the instrument, we had never previously experienced one of those in our tests.

It should be noted that maneuvers do not appear on these curves, except when there is a data gap, and therefore a reference orbit gap. On the 15th day of the arc, the apparent dip in the along-track curve is due to a lack of reference. This is repeated in the radial curve on the 22nd day.

A periodic term with a daily period and an amplitude of about 20 meters can be observed in the along-track direction. This is probably due to the oversimplification of the Earth rotation model.

Conclusion:

The TOPEX/Poseidon experiment demonstrated the good operational behavior of the on-board orbit determination software and confirmed that the orbit accuracy requirements of SPOT 4 can be met.

This experiment also demonstrated the interest of near real-time ground based processing of the DORIS data to assess the performance of the instrument, and eventually, to conduct spacecraft operations.

Current tests on 1750 emulators confirm that results of similar quality should be obtained in real-time on-board of the SPOT 4 spacecraft. If the DORIS instrument on-board of TOPEX/Poseidon had been equipped with the orbit determination card, position information with an accuracy of about 50 m rms would have been available to the spacecraft and all of its instruments since the turn-on of DORIS.

Therefore, mission designers who plan to use DORIS can count on the availability of reliable position information on-board of the spacecraft.

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